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P. Williot, Ed. Acipenser, Cemagref Publ., 1991,

ASPECTS OF THE STRUCTURE AND DYNAMICS OF AN EXPLOITED CENTRAL CALIFORNIA POPULATION OF WHITE STURGEON (*Acipenser transmontanus*)

Kohlhorst D. W.[1], Botsford L. W.[2], Brennan J.S.[3] and Cailliet G. M.[3]

[1] *Bay-Delta Project, California Department of Fish and Game*
4001 N. Wilson Way, Stockton, California 95205
[2] *Wildlife and Fisheries Biology*
University of California, Davis, California 95616
[3] *Moss Landing Marine Laboratories*
P. O. Box 450, Moss Landing, California 95039

RESUME

Le cycle de vie et la dynamique de population de l'esturgeon blanc (*Acipenser transmontanus*) de la Californie centrale ont fait l'objet d'une étude intermittente depuis 1954, date à laquelle on a rouvert la pêche d'agrément, fermée depuis 1917. Effectuées par marquage et recapture, les évaluations de population portant sur les poissons de taille minimum légale (≥ 101,6 cm de longueur totale) se sont élevées de 11.000 en 1954 à 128.000 en 1984. Le taux annuel d'exploitation s'est accru de 2% à 11,5%. Le taux moyen d'exploitation pour les années 1980 a été plus élevé de 41% que précédemment, au fur et à mesure que la pêche d'agrément est devenue, non seulement plus populaire, mais aussi plus efficace. Les évaluations concernant le taux annuel de survie sont montées de 74% à 90%, 1984 étant l'année du taux de survie le plus bas. D'après les données basées sur la récupération des plaques d'identité entre 1974 et 1988, la majorité des esturgeons blancs resteraient toute l'année dans l'estuaire et les affluents. On trouve des concentrations de poissons dans l'eau saumâtre des baies de Suisun et de San Pablo et ces poissons semblent se déplacer en amont ou en aval en fonction des changements de salinité. Les poissons adultes dans leur phase reproductive, qui représentent une faible portion des effectifs, remontent le fleuve Sacramento et, en plus petit nombre, le San Joaquin, pour frayer vers la fin de l'hiver et au printemps. Il y a un rapport positif entre le recrutement et le débit d'eau douce dans l'estuaire ; on en conclut que le contrôle de ce débit pourrait jouer un rôle important dans l'entretien des effectifs d'esturgeon. La règlementation actuelle de la pêche à la ligne a pour effet de réduire légèrement le rapport exploitation/nouveaux effectifs au-dessous du maximum, mais un autre effet est une réduction de 35% dans la production d'oeufs, en comparaison de la production observée quand l'exploitation était plus faible. De récentes augmentations du taux d'exploitation nous amènent à conclure qu'il faut imposer de nouvelles restrictions à la pêche d'agrément pour réduire la prise et protéger les poissons reproducteurs.

Mots clés : Abondance, pêche, taux de mortalité, mouvement, population, recrutement, marquage, esturgeon blanc, rendement par recrue.

ABSTRACT

Life history and population dynamics of white sturgeon (*Acipenser transmontanus*) in central California have been studied intermittently since the sport fishery was reopened in 1954 after being closed since 1917. Mark-recapture population estimates of legal-sized fish (≥101.6 cm total length) have varied from 11,000 in 1954 to 128,000 in 1984. Annual exploitation rates have ranged from 2% to 11.5%. Average exploitation rate in the 1980's has been 41% higher than in earlier years as the sport fishery has become more popular and effective. Annual survival rate estimates have varied from 74% to 90%, with lowest survival in 1984. Tag returns from 1974 to 1988 suggest that most white sturgeon remain year-round in the estuary and tributary rivers. Fish concentrate in brackish water of Suisun and San Pablo bays and appear to move up or downstream in response to salinity changes. Reproductive adults, a small fraction of the population, move upstream in the Sacramento River and, to a lesser extent, the San Joaquin River in late winter and spring to spawn. Recruitment is positively associated with the volume of freshwater flow through the estuary; hence, management of these flows may be important in maintaining the sturgeon population. The present angling regulations result in a slight reduction of yield-per-recruit below the maximum, but reduce egg production by 35% from that exhibited at previous lower exploitation rates. Recent increases in exploitation rate suggest that further restrictions on the sport fishery are needed to reduce catch and protect spawning stock.

Keywords : abundance, fishery, mortality rates, movements, population, recruitment, tagging, white sturgeon, year-class strength, yield-per-recruit.

INTRODUCTION

Description of the Sacramento-San Joaquin Estuary

The white sturgeon (*Acipenser transmontanus*) population in central California is mostly confined to the Sacramento and San Joaquin rivers and their common estuary (Figure 1). These two rivers are the largest streams in California's Central Valley and, after draining an area of about 153,000 km^2, form a tidal estuary from their junction in an inland delta to San Francisco Bay. Most of the land surface of the delta is below sea level due to years of subsidence, erosion, and oxidation of organic soils and is protected from the surrounding water by levees originally constructed in the late nineteenth and early twentieth centuries. These agricultural islands exist in a network of over 1,100 km of tidal channels varying in width from 50 m to 1.5 km and mostly less than 15 m deep. Suisun, San Pablo, and San Francisco bays downstream of the delta cover an area of about 1,125 km^2. Important marshes occur around Suisun Bay, northern San Pablo Bay, and southern San Francisco Bay. Suisun and San Pablo bays are characterized by extensive shallow flats, the higher portions of which are exposed at low tide. San Francisco Bay historically had less extensive shallow water areas than the upstream bays; shoreline landfill practices associated with urban and industrial development have further reduced the shallows in San Francisco Bay (Nichols et al., 1986).

Historically, the rivers discharged about 34 km^3 of fresh water into the estuary annually. This has been reduced by over 60% by local use along the rivers and exports to the San Joaquin Valley and Southern California (Nichols et al., 1986). Dams regulating flow in the major tributaries modify seasonal flow patterns by storing winter and spring runoff and releasing water for diversion in summer and fall. Although pulses of freshwater flow from storms continue to occur at about the same frequency as in the past (Herrgesell et al., 1983), the current level of water development has decreased the ratio of winter (Dec, Jan, Feb) to summer flow (Jun, Jul, Aug) by over 40% from the ratio without water development (calculated from data in Miller 1982). About 85% of delta inflow originates in the Sacramento River, 10% comes from the San Joaquin River, and 5% is from smaller eastern valley streams. Water is diverted all along the rivers and in the delta, primarily for agricultural use. The United States Bureau of Reclamation's Central Valley Project and California's State Water Project are the largest diverters in the system as they export water from the southern delta (Figure 1). The combined diversion rate of these projects averaged 200 m^3/s in 1987 and is authorized to increase to 270 m^3/s in 25 years (Chadwick, 1977).

A more detailed description of the Sacramento-San Joaquin Estuary is provided by Kelley (1966).

White Sturgeon in the Sacramento-San Joaquin Estuary

White sturgeon is a native anadromous fish in the Sacramento-San Joaquin Estuary and the object of an important and growing sport fishery ; commercial fishing for sturgeon is prohibited in California. Another species, the green sturgeon (*A. medirostris*), is much less common in the estuary and legal-sized ($\geq$101.6 cm total length) fish are seldom caught.

Historical accounts indicate that a commercial fishery greatly reduced the Sacramento-San Joaquin Estuary white sturgeon population in the late 1800's (Skinner, 1962). As a result, all sturgeon fishing was prohibited in 1917 ; the fishery was reopened to sport angling only in 1954. With the exception of the period from 1956 to 1963 when the minimum size limit was raised to 127 cm total length (TL), the sport fishery has had

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the same regulations since its inception : a year-round season, 101.6 cm TL minimum size limit, and a one fish per day creel limit.

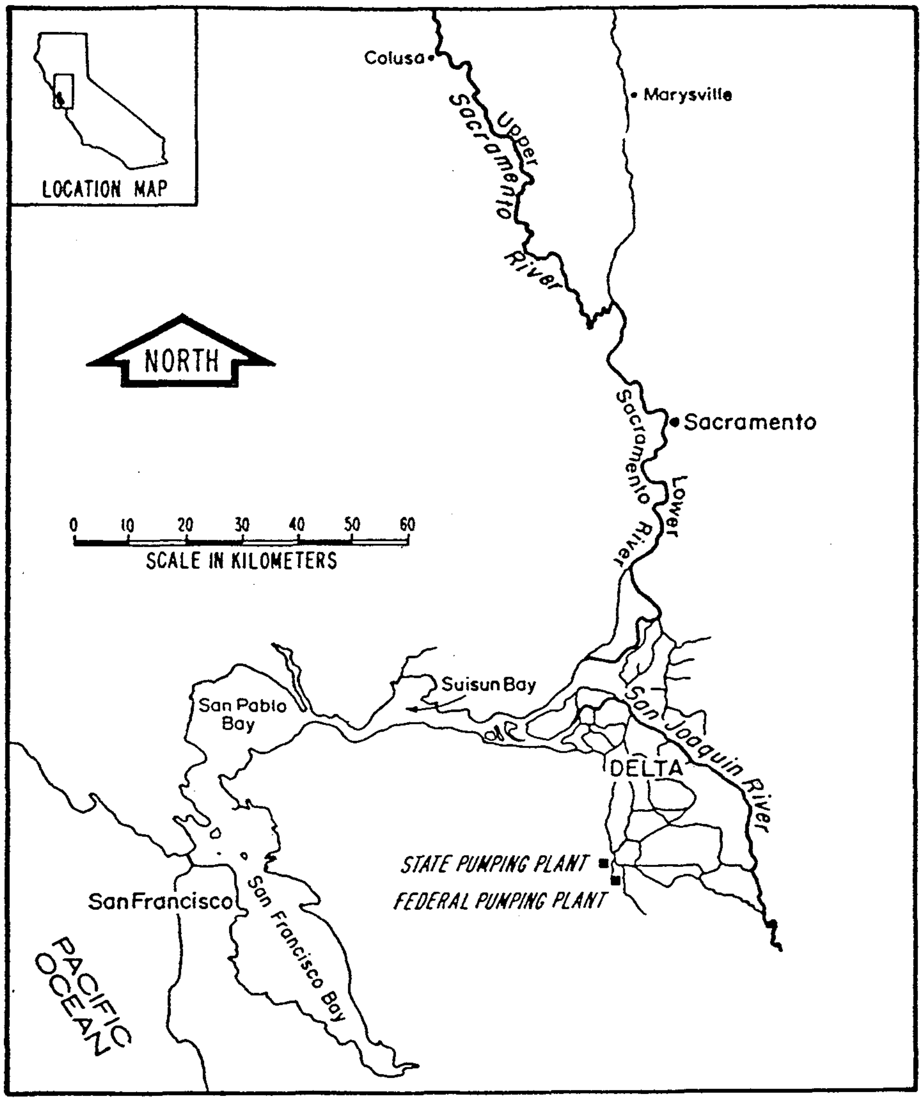

Figure 1 - The primary area inhabited by white sturgeon in California

Initially, the sport fishery was unsuccessful because angler interest was low and effective angling techniques had not been developed. However, in 1964 fishing success improved dramatically when shrimps, *Crangon spp.* and *Palaemon macrodactylus* were first used as bait. Since then, burrowing shrimps of the genera Callianassa and *Upogebia* also have been widely employed as sturgeon bait.

White sturgeon life history and population dynamics have been studied intermittently since the sport fishery reopened in 1954. The general time and location of spawning in the Sacramento River have been described (Stevens and Miller, 1970 ; Kohlhorst, 1976), as have food habits of juveniles (Schreiber, 1962; Radtke, 1966) and adults (McKechnie and Fenner, 1971) and growth rate (Kohlhorst et al., 1980; Brennan and Cailliet, in press). Tagging studies (Pycha, 1956; Chadwick, 1959; Miller, 1972 a, b; Kohlhorst, 1979, 1980; Brennan and Cailliet, 1991) have been used to estimate abundance and mortality rates, to describe movements, and to validate aging techniques.

This report summarizes and updates these abundance and mortality rate estimates through 1988, describes general movement patterns since 1974, examines the effect of hydrologic variables on year class strength, and estimates the effect of sport angling regulations on yield.

METHODS

Tagging

A tagging study was used to obtain mark-recapture estimates of white sturgeon abundance, exploitation rate, survival rate, and movement pattern. In 1954 and 1974, pectoral fin rays were removed from some tagged fish for the purpose of age determination. Tagging methods and results before 1984 were originally reported by Pycha (1956), Chadwick (1959), Miller (1972a, 1972b), and Kohlhorst (1979, 1980), Kohlhorst et al. (1980), and Shirley (1987). Some earlier results are presented here for comparison with recent estimates. The following tagging methods are those used in 1984, 1985, and 1987.

Sturgeon to be tagged were captured in a 20.3 cm stretched mesh trammel net, 366 m long and 6 m deep, that was drifted in the fall in San Pablo Bay (and occasionally in Suisun Bay) (Figure 1). Drifts lasted from 1/4 to 2-1/2 h. Sturgeon were removed from the net, placed in fabric or plastic cradles, and tagged with disc-dangler tags attached with stainless steel wire through the muscle below the anterior end of the dorsal fin using methods described by Chadwick (1963). Twenty-dollar reward tags were used exclusively to assure a high rate of response from anglers catching tagged sturgeon. Only legal-sized fish were tagged. After being tagged and measured to the nearest centimeter total length, fish were immediately released near the site where they were captured.

As part of a study to validate sturgeon aging techniques, some fish each year were injected with oxytetracycline (OTC) at the time of tagging (26% of the tagged fish in 1984, 31% in 1985, and 79% in 1987) (Brennan and Cailliet, 1991). Injected fish were double-tagged with T-bar disc or spaghetti tags in 1984 and 1985, but most of these second tags were shed in the first year after release and were not used in any analysis presented here. All fish were single-tagged in 1987.

Mean total length of tagged fish was calculated for each tagging year from 1974 to 1987. The statistical significance of differences in mean size was tested using one-way ANOVA and Tukey's multiple comparison test (Zar, 1984).

Abundance

In 1984 and 1985, white sturgeon abundance was estimated using Bailey's (1951) modification of the Petersen method because a recapture sample was available from a later year. In 1987, the multiple census method of Schumacher and Eschmeyer (Ricker, 1975) was used because recaptures during tagging were all that were available. Confidence intervals for the Petersen estimates were calculated by assuming tag recaptures followed a Poisson distribution and, for the Schumacher and Eschmeyer estimate, by following Ricker (1975). Abundance estimates before 1984 used one of the above methods, depending on the availability of a recapture sample in subsequent years (Kohlhorst 1980). The assumptions inherent in any mark-recapture experiment are described by Ricker (1975) and Kohlhorst (1980) discusses potential biases in the multiple census technique as applied to white sturgeon. Assumptions of random distribution of tagged fish in the untagged population and equal vulnerability of tagged and untagged fish to the fishing gear are likely violated by the multiple census techniques. Both methods deal with a population that is probably not closed and the proportion of the entire population represented by the estimate is unknown and may vary between estimates.

Abundance was also indexed using catch per net-h during tagging as described by Kohlhorst (1980) for 1967-1979. Here, we add values for 1984-1987.

Exploitation Rate

Exploitation rate was estimated as R_1/M, where R_1 = the number of tags returned by anglers in the first year after tagging and M = the number of fish tagged. We assumed that the use of reward tags assured a 100% reporting rate for all tagged fish recovered by anglers. Exploitation rate estimates would be biased low by failure of this assumption or by unrecognized tagging mortality. Confidence intervals for exploitation rate estimates were calculated assuming a Poisson distribution for tag recoveries (Ricker, 1975). When return rate for OTC-injected fish and uninjected fish differed, the higher return rate was used as the estimate of exploitation rate.

Survival Rate

We estimated annual survival rate for the one-year period following tagging in 1984 with a bias-adjusted maximum likelihood equation (Model 1 of Brownie et al., 1978) applied to returns from 1984 and 1985 tagging.

When a maximum likelihood estimate of survival rate could not be obtained because tagging was not conducted in two successive years, we determined average annual survival rate from a catch curve (Ricker, 1975) using age frequencies of tagged sturgeon. Ages were estimated from length frequencies with an age-length key based on sturgeon aged in 1973-1976. The slope of the straightest portion of the descending right limb of the curve was calculated using regression of the natural logarithm of numbers on age. The antilog_e of the slope is an estimate of survival rate.

Movements

We described movement patterns by recording the month and location of tag recovery reported by anglers from 1974 to 1988. Tag return data were combined to provide a general picture of movement and examined separately by recovery year to detect variations or trends in movement patterns.

Young White Sturgeon Abundance and Year Class Strength

Young-of-the-year and juvenile (ages 1-5) white sturgeon were captured with otter and midwater trawls fished once monthly at 35 locations from southern San Francisco Bay to the western delta (Figure 1) from 1980 to 1987. The semiballon otter trawl (4.9 m mouth opening, 2.5 cm stretched-mesh body, 1.3 cm stretched-mesh cod end) was towed on the bottom for 5 min at each location. The midwater trawl (3.7 m by 3.7 m mouth opening with variable mesh from 20.3 cm stretched-mesh at the mouth to 1.3 cm stretched-mesh at the cod end) was fished in a diagonal tow from bottom (or 12.2 m, whichever was shallower) to surface for 10 min at each location. Captured white sturgeon were measured to the nearest millimeter fork length.

Approximate age was assigned using the Von Bertalanffy growth curve for white sturgeon (Kohlhorst et al., 1980) after first converting fork length to total length by multiplying by 1.08. Abundance and distribution were examined for annual variability and trends.

An index of year class strength for year i was calculated as :

$YCI_i = \Sigma N_o/y$, where
y = number of years in which fish of year class i were available to the sampling gear at ages 0-5 and
$N_o = N_t/e^{-Zt}$, where
t = age at capture,
N_t = number captured at age t,
Z = assumed instantaneous mortality rate of 0.2877 (equivalent to annual survival rate of 0.75), and
N_o = backcalculated catch at age 0 that would be the equivalent of N_t.

With this method, the more ages at which each year class is sampled, the more reliable the estimate of YCI.

Associations between YCI and hydrologic variables (mean daily freshwater outflow from the estuary, mean daily freshwater diversions from the delta, and mean daily percent of inflow diverted) were explored with correlation analysis. These environmental variables were chosen because they affect the production of young by other anadromous fishes in the estuary (Turner and Chadwick, 1972; Stevens, 1977; Stevens and Miller, 1983; Stevens et al., 1985).

Effect of Angling Regulations

To estimate the relative effects of different regulations on yield we computed yield-per-recruit in terms of biomass for various lower size limits and fishing mortality rates. In addition, to evaluate the potential effects of regulations on future recruitment, we computed eggs-per-recruit for various size limits and fishing mortality rates. Because of a paucity of fecundity and spawning frequency data for this population, we have assumed egg production is proportional to weight for these calculations.

RESULTS

Tagging

We tagged a total of 5,952 white sturgeon in 1984, 1985, and 1987 (Table 1). Mean total length of tagged fish since 1974 has ranged from 121 to 135 cm. Fish tagged in 1979 and 1984 were significantly smaller than in other years since 1974 and fish tagged in 1974 were significantly larger ($p<0.001$).

Table 1 - Number, size, and tag reward value of white sturgeon tagged in the Sacramento-San Joaquin Estuary from 1954 to 1987. Only legal-sized (≥ 101.6 cm total length) fish are included. Values for years before 1974 are from Pycha (1956) and Miller (1972a). Kohlhorst (1979, 1980) reported some of the values for 1974 and 1979

Year	Number Tagged	Total Length (cm)			Reward Tag Value($)
		Mean	Range	Conf. Int.[1] (95 %)	
1954	994	145	102-239	-	0
1967	1,612	119	102-163	-	5
1968	1,080	124	102-163	-	5
1974	713	134.7	102-239	133.2-136.2	5
1979	1,368	121.4	102-202	120.5-122.2	10
1984	2,551	122.3	102-272	121.8-122.9	20
1985	2,419	126.2	102-214	125.6-126.8	20
1987	982	126.0	102-225	124.9-127.1	20

[1] Conf. Int. = Confidence Interval

Abundance

White sturgeon abundance estimates have varied substantially since 1954 (Table 2). The lowest estimated population of 11,000 legal-sized fish in 1954 (Pycha, 1956) increased about 10 times to 115,000 (Miller, 1972a) by 1967 and then decreased again to 21,000 in 1974 (Kohlhorst, 1980). Kohlhorst's results indicated another increase to 74,000 fish in 1979. Recent tagging results show abundance reaching the highest level yet estimated (128,000) in 1984 followed by a decrease to 96,000 in 1985 and 84,000 in 1987.

As reported by Kohlhorst (1980), catch per net-h followed a pattern generally similar to the abundance estimates, although the correlation between these two measures of abundance is not statistically significant ($r=0.62$, $n=7$, $p>0.10$). Notable differences in the pattern of change shown by these two measures of abundance occurred in 1968 and 1987 (Table 2). In 1968 the multiple census estimate decreased from the previous year while catch per net-h increased and in 1987 catch per net-h decreased relatively more than the multiple census estimate.

Table 2 - White sturgeon tagging results for the Sacramento-San Joaquin Estuary from 1954-1987. All values pertain to legal-size (≥ 101.6 cm total length) fish only. Results for years before 1984 were originally reported by Pycha (1956), Chadwick (1959), Miller (1972a), and Kohlhorst (1979, 1980).

Year	Catch per Net-h	Abundance: Estimate	Abundance: 95% Conf. Int[3].	Exploitation Rate: Estimate	Exploitation Rate: 95 % Conf. Int.[3]	Survival Rate: Estimate	Survival Rate: 95 % Conf. Int.[3]
		$\times 10^3$	$\times 10^3$	$\times 10^{-3}$	$\times 10^{-3}$		
1954	-	11.2	8.8-15.7	20	13-31	-	-
1967	15.3	114.7	72.4-212.3	73	58-88	0.84[1]	0.65-1.03
1968	19.5	40.0	29.2-63.5	65	49-83	-	-
1974	3.7	20.7	13.1-50.1	56	36-84	0.90[2]	0.82-0.99
1979	8.4	74.5	53.3-123.3	83	68-98	0.82[2]	0.78-0.87
1984	36.2	128.3	100.6-170.0	89	68-114	0.74[1]	0.64-0.84
1985	18.2	96.2	64.2-157.9	115	90-141	0.84[2]	0.80-0.89
1987	6.7	84.0	46.8-411.4	87	67-110	0.86[2]	0.82-0.90

[1] Maximum likelihood estimates from tag returns
[2] Catch curve estimates from age frequencies of tagged fish
[3] Conf. Int. = confidence interval

Exploitation Rate

Based on estimates from 1984, 1985, and 1987 tagging, annual exploitation rate has ranged from 0.087 to 0.115 recently (Table 2). This is higher than previous estimates, and the trend in exploitation rate (with 1954 omitted since present fishing techniques were not in use then) is almost statistically significant ($F=6.46$; $df=1,5$; $p=0.052$).

Survival Rate

Survival rate estimates have been remarkably uniform over the period of record (Table 2). The maximum likelihood estimate of 0.74 in 1984 is the lowest that we have observed. The catch curve estimates of survival (1974, 1979, 1985, 1987) exhibit little variability, possibly because they are essentially averages over several years (Figure 2, Table 2). The greater precision of the catch curve estimates, reflected in the narrow confidence intervals, does not imply greater accuracy of these estimates in relation to the maximum likelihood estimates.

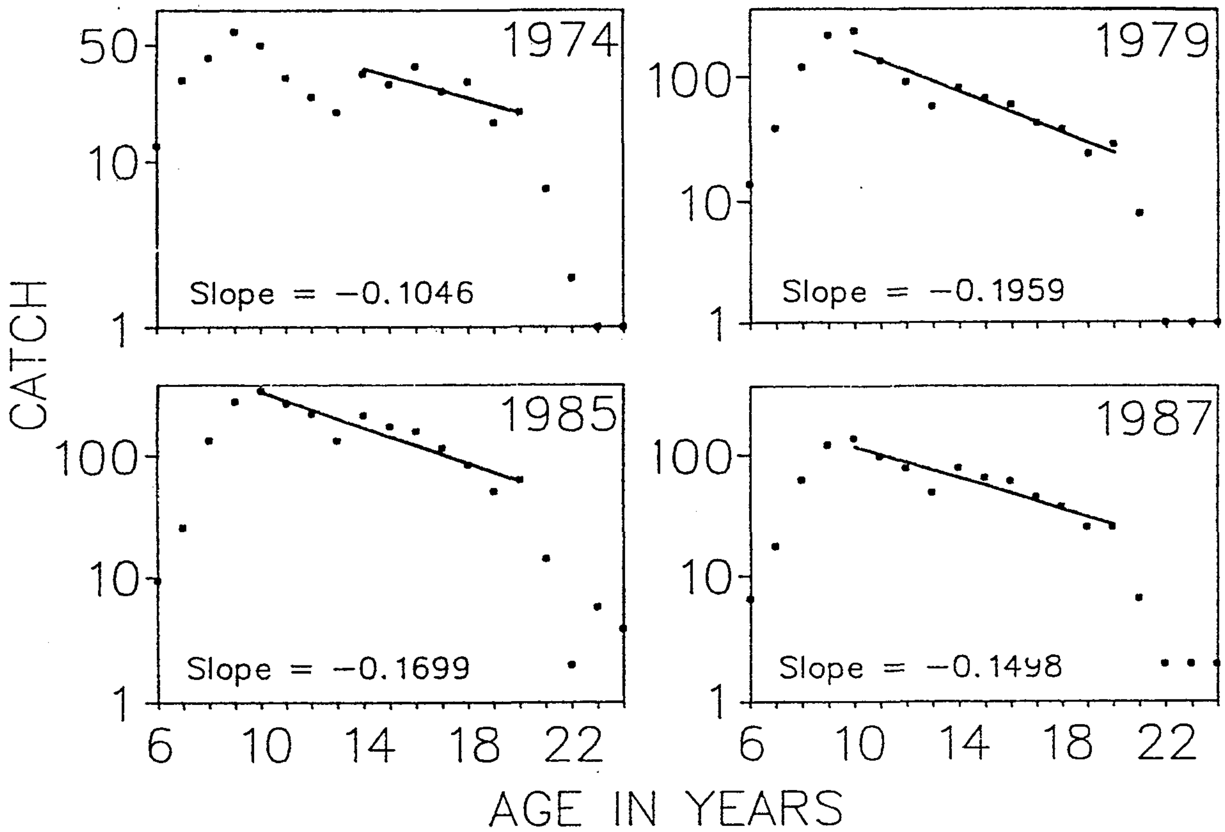

Figure 2 - Catch curves for white sturgeon tagged in the Sacramento-San Joaquin Estuary in 1974, 1979, 1985 and 1987. The slope of the straightest segment of the descending right limb of the curves was used to estimate annual survival rate. The slope of each line is shown. Survival rate = antilog$_e$ (slope). Note that the y-axis scale for 1974 is different from the other years.

Movements

A total of 1,455 white sturgeon tags returned by anglers between 1974 and 1988 was used to describe movement patterns. Over 66% of the tag returns were received from the Suisun and San Pablo Bay area (Table 3). Many sturgeon are found in these two bays throughout the year, but peak fishing in Suisun Bay occurs from November through January ; it occurs from January through March in San Pablo Bay. In San Francisco Bay, over half the annual catch is taken from January through March and almost no fish are caught from August through October.

Some sturgeon move into the lower Sacramento River and the delta in fall and their numbers increase in winter (Table 3). A portion of these fish, presumably those that are mature and ready to spawn, move up the Sacramento River until they are concentrated in the upper river near Colusa (Figure 1) from March through May. The mean total length at tagging of white sturgeon caught in the upper Sacramento River was 145 cm; this is significantly greater ($p<0.05$) than the mean length of 125 cm for the entire tagged sample. As most female white sturgeon in the Sacramento-San Joaquin Estuary do not mature until they reach about 135 cm (Calif. Dept. Fish and Game, unpublished), the large size of fish in the Sacramento River and the known spawning period of late February through May (Kohlhorst, 1976) indicate that the movement up the Sacramento River is a spawning migration.

Movement of white sturgeon into the San Joaquin River in the spring (Table 3) suggests spawning occurs there also, although no sampling to collect sturgeon eggs or larvae has been done in the San Joaquin system. If the number of tag returns from each river is a valid indicator of the relative number of spawning fish, over ten times (spring tag return ratio of 53:5; Table 3) as many white sturgeon spawn in the Sacramento River as in the San Joaquin River. Flows in the San Joaquin River are only about 1/8 those in the Sacramento River.

In recent years, some white sturgeon have moved out of the estuary and migrated up the coast to Oregon and Washington. Chadwick (1959) reported one white sturgeon tagged in 1954 was returned from the Columbia River, Oregon, but no additional evidence of coastwise migration was seen until 1985 when a white sturgeon tagged in 1979 was captured in the Chehalis River, Washington. Since then, 11 more tagged white sturgeon have been caught in six river systems north of California, primarily the Umpqua River, Oregon (five tags recovered) and the Chehalis River, Washington (three tags). Also, one tag return each was received from the Columbia River, Yaquina River, and Tillamook Bay, Oregon and the Willapa River, Washington.

Table 3 - Returns by area and month for white sturgeon tagged in the Sacramento-San Joaquin Estuary and recovered by anglers from 1974 to 1988.

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
Washington	-	-	-	-	-	-	2	2	-	-	-	-	4
Oregon	-	2	1	2	-	1	2	-	-	-	-	-	8
Pacific Ocean	-	-	1	-	-	-	-	-	-	-	-	-	1
San Francisco Bay	51	45	81	44	18	5	2	1	1	1	13	43	305
San Pablo Bay	61	[illegible]	111	39	37	21	13	8	10	18	23	55	465
Suisun Bay	65	38	39	32	32	42	31	28	27	42	58	71	505
Lower Sacramento River	13	16	11	6	3	2	-	-	1	3	5	7	67
Delta	4	-	3	3	1	1	-	-	3	2	6	5	28
Sacramento River	1	-	5	4	2	-	-	-	-	-	-	2	14
Upper Sacramento River	3	2	12	23	8	3	-	-	-	-	-	2	53
San Joaquin River	-	-	3	1	1	-	-	-	-	-	-	-	5
TOTAL	198	172	267	154	102	75	50	39	42	66	105	185	1455
PERCENT OF TOTAL	13.6	11.8	18.4	10.6	7.0	5.2	3.4	2.7	2.9	4.5	7.2	12.7	

White sturgeon appear to move within the estuary in response to flow, which affects salinity, so that they are farther upstream when saline water encroaches eastward in dry years and farther downstream when brackish water is pushed westward in wet years. In dry years, when freshwater flow was low and salt water encroached upstream, such as 1976, 1977, and 1985, more sturgeon were found in Suisun Bay and fewer in San Pablo Bay than in other years (Figure 3). In wet years with high freshwater flows such as 1978, 1980, 1982, and 1986, more fish were recaptured in San Pablo Bay. The percentages of annual tag returns from these two bays are significantly correlated (Suisun Bay : $r=-0.64$, $n=13$, $p<0.02$; San Pablo Bay :

r=0.80, n=13, p<0.01) with year type when year type is quantified by ranking from critically dry (1) to wet (4). More fish also tend to use San Francisco Bay in wet years, but the association between the percent of annual returns from there and ranked year type was not significant (r=0.39, n=13, p>0.10).

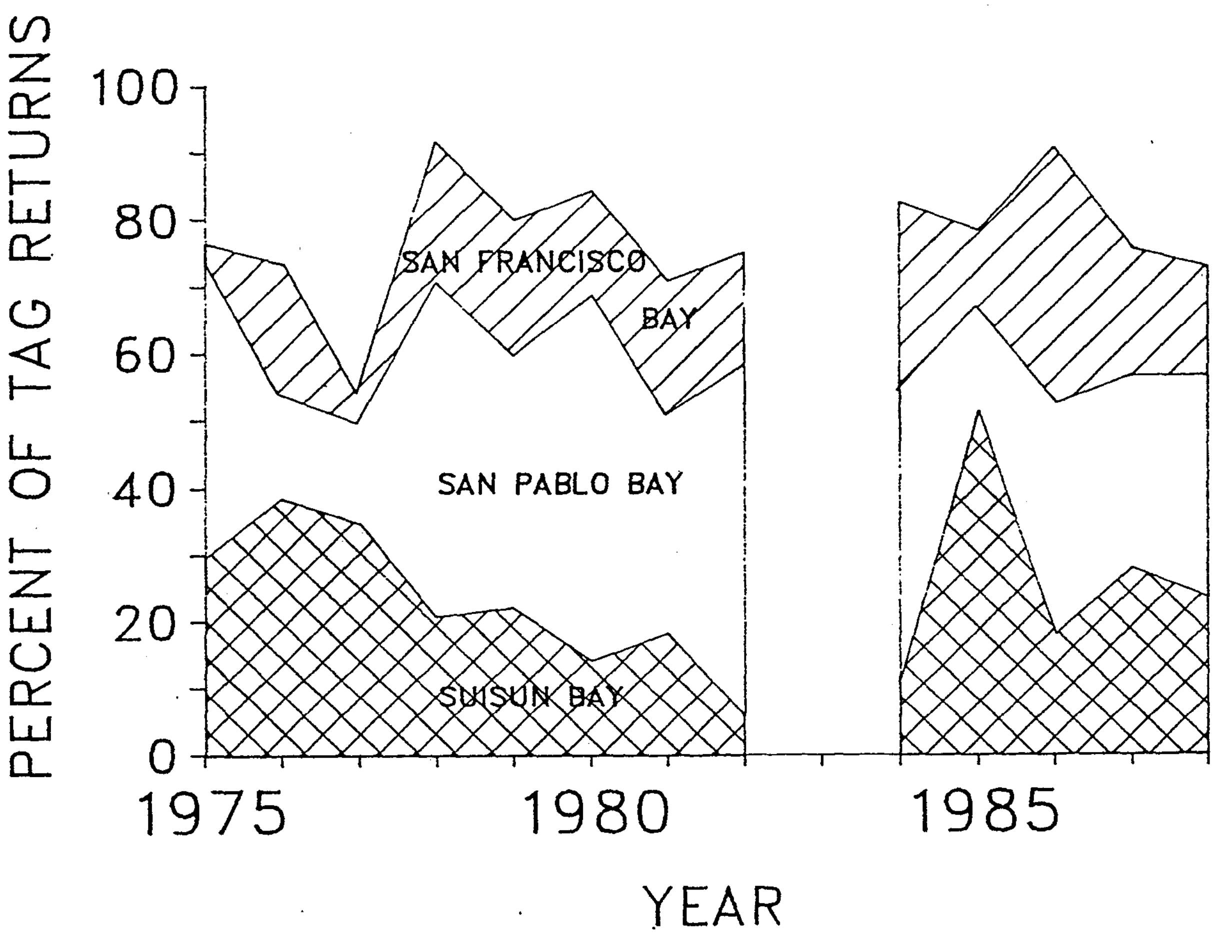

Figure 3 - Annual percent of white sturgeon tag returns by sport anglers from Suisun, San Pablo, and San Francisco bays in the Sacramento-San Joaquin Estuary. We omitted 1983 because only 17 tags were returned that year.

Young White Sturgeon Abundance and Year Class Strength

A total of 429 white sturgeon was captured in otter and midwater trawls from 1980 to 1987. These fish ranged from 31 to 1,382 mm total length (Figure 4), but fish greater than age 5 (approximately 815 mm) were omitted when indexing year class strength for 1975 to 1986. Estimated production from the 1982 and 1983 year classes was substantially greater than for other years in this period (Figures 4 and 5). These were both years of very high spring and early summer freshwater outflow from the estuary and are responsible for the significant (p<0.001) correlation between year class index and outflow in all months from April to July (Table 4, Figure 5). These correlations with mean daily flow decreased slightly from April to July, suggesting spring flow affects production more than summer flow. Correlations of the year class index with the mean daily volume of diversions by the State and Federal water projects and delta agriculture were not significant. Negative correlations with the percent of inflow that is diverted increased from March to July, but only the July value was significant (p<0.001).

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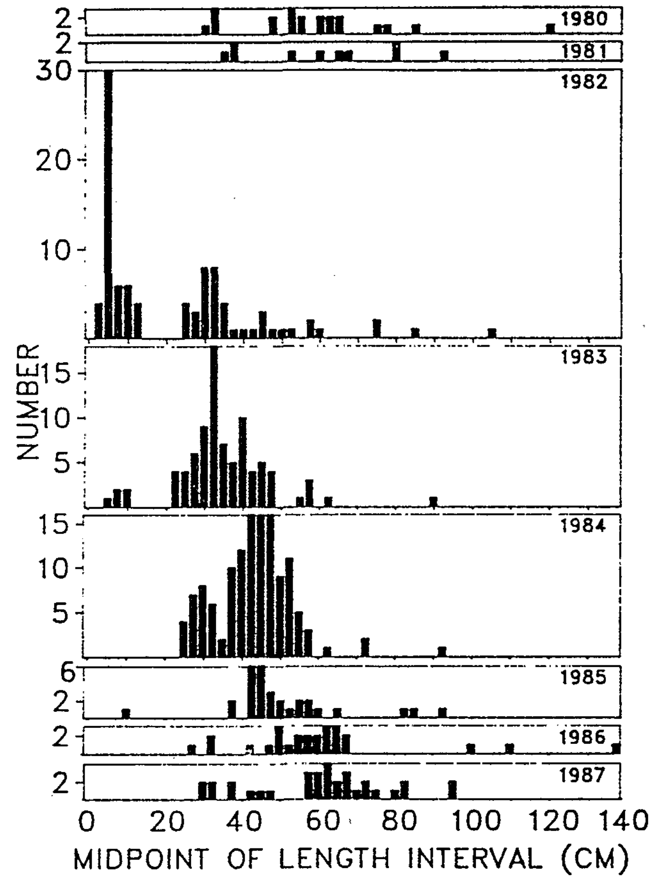

Figure 4 - Annual length frequencies of white sturgeon caught in otter and midwater trawls in the Sacramento-San Joaquin Estuary from 1980 to 1987.

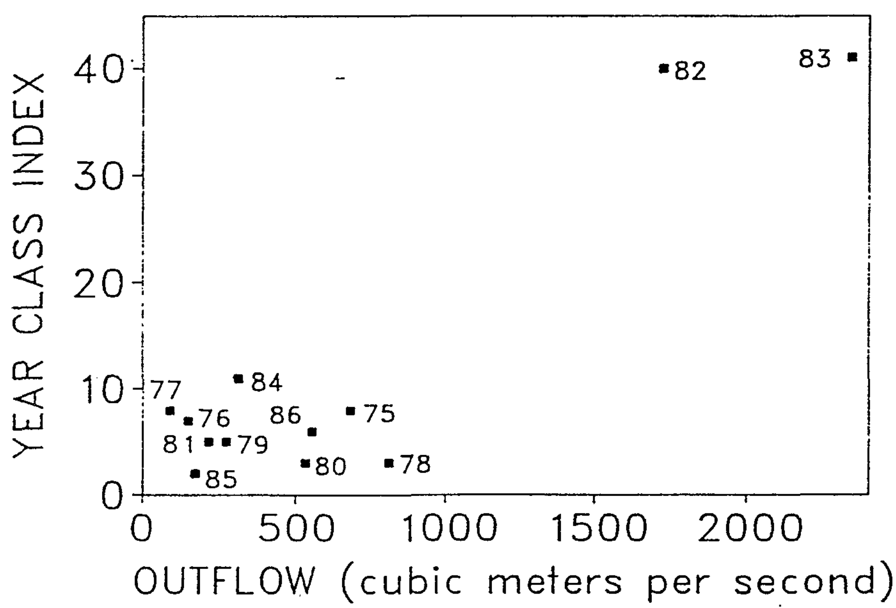

Figure 5 - Scatterplot of white sturgeon year class index versus mean daily outflow for April to July in the Sacramento-San Joaquin Estuary. Numbers adjacent to points designate year classes.

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Table 4 - Product-moment correlation coefficients between the white sturgeon year class index and hydrologic variables in the Sacramento-San Joaquin Estuary for the years 1975-1986. *Asterisks* denote statistical significance at the 0.001 level. Experimentwise error rate over all 21 correlations is approximately 0.02. Mean daily values are used for all hydrologic variables.

Variable	Correlation with Year Class Index
March Outflow	0.579
April Outflow	0.882*
May Outflow	0.842*
June Outflow	0.831*
July Outflow	0.828*
April-May Outflow	0.890*
May-June Outflow	0.849*
June-July Outflow	0.833*
April-May-June Outflow	0.898*
May-June-July Outflow	0.852*
April to July Outflow	0.903*
March Diversions	0.379
April Diversions	0.209
May Diversions	-0.097
June Diversions	-0.234
July Diversions	-0.376
March % of Inflow Diverted	-0.231
April % of Inflow Diverted	-0.423
May % of Inflow Diverted	-0.445
June % of Inflow Diverted	-0.678

Effect of Angling Regulations

Yield-per-recruit calculations indicate that observed values of instantaneous fishing mortality rate and minimum size limit are near a relatively flat part of the yield surface ; hence, biomass yield is relatively insensitive to small changes in these parameters (Figure 6). For earlier fishing mortality rates (0.06), the size limit that would produce maximum yield was near 120 cm, but the existing limit (101.6 cm) reduces yield only 3%. For more recent fishing mortality rates (0.09), a size limit of 130 cm maximizes yield, but the existing size limit reduces yield only 8%.

In addition to maintaining high yields per recruit, we also wish to maintain high recruitment rates. Because the relationship between stock and recruitment is not known for white sturgeon, we have resorted to the goal of providing for adequate egg production (Botsford and Hobbs 1986). On the basis of egg-per-recruit calculations, the recent increase in instantaneous fishing mortality rate (from 0.06 to 0.09) has reduced egg production by 35%.

Returning to the previous level of egg production would require either :
(1) increasing the size limit to 130 cm,
(2) returning fishing mortality rate to its former value, or
(3) a combination of changes such as increasing the size limit to 120 cm and reducing instantaneous fishing mortality rate to 0.075.

The first would increase biomass yield by 8%, the second would reduce yield by 7%, and the third would increase yield by 3%.

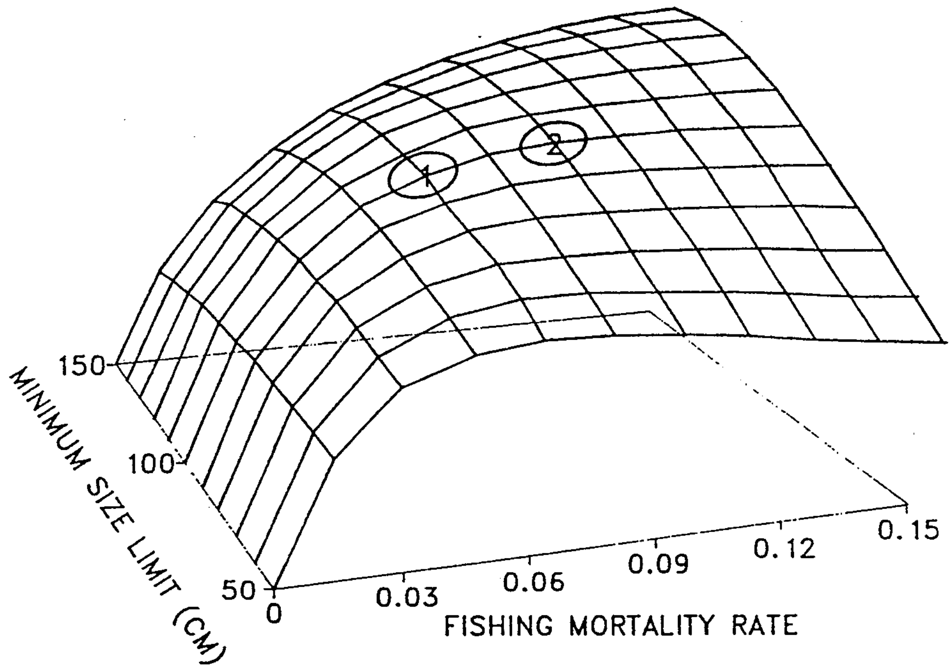

Figure 6 - Biomass yield for the Sacramento-San Joaquin Estuary population of white sturgeon. Ellipse 1 reflects fishing mortality rates in the 1960s and 1970s and ellipse 2 reflects current higher fishing mortality rates.

DISCUSSION

White sturgeon abundance in the Sacramento-San Joaquin Estuary has varied dramatically in the last 35 years, while total mortality rates during much of that period have been relatively stable. This suggests that the abundance of legal-sized sturgeon has been controlled primarily by variations in recruitment. If, like many other fishes, white sturgeon year class strength is set early in life, then recruitment is directly related to previous production of young fish.

We have presented evidence that the production of young sturgeon may be associated with freshwater outflow from the estuary ; in years with very high outflow in spring and early summer, more young-of-the-year sturgeon are produced. Year class strength may also be weakly associated with the fraction of freshwater inflow to the estuary that is diverted in the delta, but this is likely the result of an inverse relationship between percent diverted and flow when diversions are relatively constant, as they were for the 1975-1986 period when year class indices are available. The association of sturgeon year class strength with outflow is consistent with relationships observed for several other anadromous species inhabiting the estuary, specifically striped bass (*Morone saxatilis*) (Turner and Chadwick, 1972; Stevens et al., 1985), chinook salmon (*Onchorynchus tshawytscha*), American shad (*Alosa sapidissima*), and longfin smelt (*Spirinchus thaleichthys*) (Stevens and Miller, 1983). High flows may improve young sturgeon survival by transporting larvae to areas of greater food availability, by dispersing larvae over a wide area of the rivers and estuary to take advantage of all available habitat, by quickly moving larvae downstream of any influence of water diversions in the delta, or by enhancing productivity in the nursery area by increasing the nutrient supply. Additionally, adults may experience a stronger attraction to upstream spawning areas in high flow years and spawn in greater numbers.

While we have demonstrated an association between year class strength and outflow, data are inadequate to evaluate the nature of the spawner-recruit relationship. In this regard, a time series of recruitment estimated from aged samples collected from the population at four times between 1954 and 1986 depicts a large peak in recruitment in 1938, a broader peak in the mid-1950s and an even broader peak in the late 1960s (Figure 7) (Shirley 1987). This pattern is consistent with an "echo effect" (Leslie 1945 ; Bernardelli 1941) for a species that matures at about age 14. It reflects decaying peaks in reproduction that result from a large recruitment with a positive influence of adult numbers on recruitment. Given this suggestion of a spawner-recruit relationship, it seems prudent, for management purposes, to make the conservative assumption that spawning stock, as well as environmental factors, influence recruitment.

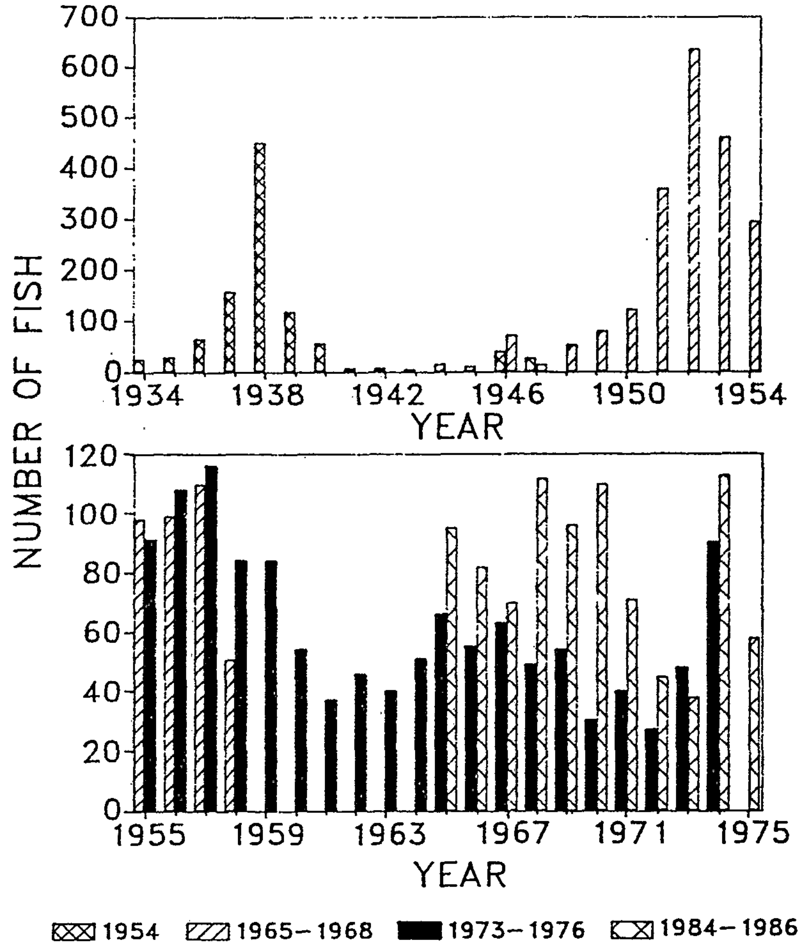

Figure 7 - Recruitment time series from white sturgeon captured in the Sacramento-San Joaquin Estuary in 1954, 1965-1968, 1973-1976, and 1984-1986 plotted on the same axis. Note change of scale on the y-axis between graphs (from Shirley 1987).

Fluctuations in legal-sized white sturgeon abundance have been dependent on recruitment, and not mortality, because mortality rates have been low and relatively stable over most of the period of record. However, mortality now may be increasing. Annual exploitation rate, a major component of total annual mortality rate, has increased from a mean of 0.069 in the 1960's and 1970's to 0.097 in the 1980's. This 41% increase in harvest rate has resulted from burgeoning popularity of the fishery and greater sophistication of anglers in locating fish with sonar and inducing them to bite. The increase in maximum likelihood estimates of annual mortality rate from 0.16 (survival = 0.84) in 1967 to 0.26 (survival = 0.74) in 1984 hints at the effect of the expanded fishery on the sturgeon population, although the correlation between exploitation rate and total mortality rate ($r=0.38$, $n=6$, $p>0.10$) is not statistically significant.

Our knowledge of the dynamics of the white sturgeon population in the Sacramento-San Joaquin Estuary has implications for water development and management and for fishery management: flows must be adequate to maintain recruitment and fishing regulations must offer sufficient protection to keep harvest rates low and maintain spawning stocks. Unfortunately, data on year class strength are still inadequate (Figure 5) to specify to agencies that regulate water development the flow requirements that are necessary to optimize sturgeon production. We can only qualitatively observe that high flows produce good year classes. Because of this insufficient knowledge, the California Department of Fish and Game has initiated a program to develop better indices of year class abundance from catches of 1- to 5-year-old sturgeon captured in a small-mesh gill netting survey centered in Suisun Bay. Anticipated large catches of juveniles in this gear should yield more reliable indices than provided by the relatively low trawl catches and should allow better quantification of the relationship between year class strength and environmental variables.

Changes in angling regulations to reduce white sturgeon harvest are in order. While we do not know exactly the maximum harvest that the population can support without affecting both present status and future recruitment, the 40% increase in annual harvest rate in the 1980's and its predicted effect on egg production are cause for concern. Sturgeon are readily vulnerable to overharvest and subsequent decline (Bijkov, 1949 ; Dees, 1961) because they cannot rapidly compensate for unusually high mortality. To reduce the possibility of lower future recruitment we wish to maintain egg production at an adequate level. Changes in angling regulations that are being considered to attain this objective include increasing the minimum size limit, imposing a maximum size limit, initiating a "slot limit" that would protect fish in a given size range, and season or area closures.

In the future, management of the white sturgeon resource may require new approaches. These include evaluating the sensitivity of conclusions to parameter estimates and evaluating yield in terms other than biomass, which may not be the best indicator of value for a recreational fishery. In addition, we might attempt to regulate the population at the size limit and mortality rate that maximized yield under the constraint that the current (or higher) level of egg production be maintained (Botsford and Hobbs, 1987). However, even maintaining egg production at a specified level does not guarantee persistence of the population; we must also consider changes in the age structure. Broad, flat age structures provide more stable populations and lower extinction probabilities than narrow peaked ones (Botsford, 1986 ; Murphy, 1968) in variable environments. In addition to the effects of increased harvest on this population, we will consider, in this context, the influences of changes in the random environment as it affects sturgeon recruitment, particularly changes in magnitude and variability of freshwater flows.

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